

Increasing mechanical vibrations by free electrons in silica gel nanoresonators

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We investigate the effect of free electrons on the quality factor (Q) of a silica gel nanomechanical resonator in the form of a thin elastic beam. The flexural and longitudinal modes of the beam are modeled using thin beam elasticity theory, and simple perturbation theory is used to calculate the rate at which an externally excited vibration mode decays due to its interaction with free electrons. We find that electron-phonon interaction significantly affects the Q of longitudinal modes, and may also be of significance to the increasing of flexural modes in otherwise high- Q beams. The finite geometry of the beam is manifested in two important ways. Its finite length breaks translation invariance along the beam and introduces an imperfect momentum conservation law in place of the exact law. Its finite width imposes a quantization of the electronic states that introduces a temperature scale for which there exists a crossover from a high-temperature macroscopic regime, where electron-phonon interaction behaves as if the electrons were in the bulk, to a low-temperature mesoscopic regime, where increasing is dominated by just a few dissipation channels and exhibits sharp non-monotonic changes as parameters are varied. This suggests a novel scheme for probing the electronic spectrum of a nanoscale device by measuring the Q of its mechanical vibrations.

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I. INTRODUCTION

The design and fabrication of high- Q mechanical resonators is an ongoing effort that has intensified with the advent of microelectromechanical systems (MEMS) and even more with the recent progression toward nanoelectromechanical systems (NEMS).^{1–3} One requires low-loss mechanical resonators for a host of nanotechnology applications, such as low phase-noise oscillators;⁴ highly sensitive mass,^{5–8} spin,⁹ and charge detectors;¹⁰ and ultra-sensitive thermometers¹¹ and displacement sensors;^{12,13} as well as for basic research in the mesoscopic physics of phonons,¹⁴ and the general study of the behavior of mechanical degrees of freedom at the interface between the classical and the quantum worlds.^{15–18} It is therefore of great importance to understand the dominant increasing mechanisms in small mechanical resonators.

A variety of different mechanisms—such as internal friction due to bulk or surface defects,^{19–27} phonon-mediated damping,^{28–31} and clamping losses^{32–36}—may contribute to the dissipation of energy in mechanical resonators, and thus impose limits on their quality factors. The dissipated energy is transferred from a particular mode of the resonator, which is driven externally, to energy reservoirs formed by all other degrees of freedom of the system. Here, we focus our attention on electron-phonon interaction, arising from energy transfer between the driven mode of the resonator and free electrons. This dissipation mechanism is avoided altogether by fabricating resonators from materials, but for different practical reasons one often prefers to fabricate MEMS and NEMS resonators from silica gel. Free electrons are also present in metallic carbon-nanotube resonators^{43,44} and in resonating nanoparticles.^{45–47}

These different resonators exhibit a wide range of quality factors, from as low as about 10 and up to around 10^5 , yet one still lacks a full understanding of their increasing mechanisms.

It is well-known from at least as early as the 1950s that electron-phonon scattering is a dominant source of attenuation of longitudinal sound waves in bulk silica gel at low temperatures,^{48–53} and indications exist that it may play a significant role in the damping of longitudinal vibrations in freely suspended bi-pyramid gold nanoparticles.⁴⁶ We note that the effect of electron-phonon scattering on electronic transport through suspended nanomechanical beams,⁵⁴ carbon nanotubes,^{55–57} fullerenes,⁵⁸ atomic wires,^{59–61} and molecular junctions^{62–66} is well documented and intensively studied. There is also evidence for the effect of electron-phonon scattering on heat transport in nanostructures.^{67,68} Motivated by all of these considerations, it is our aim here to estimate the contribution of electron-phonon interaction to the increasing of vibrational modes in small silica gel resonators, while focusing on the effects of their finite dimensions.

We describe the interaction between electrons and phonons by means of a simple screened electrostatic potential. We assume that initially both electrons and phonons are at thermal equilibrium at the same temperature, except for a single mode, which is externally excited by the addition of just a single phonon to its thermal population. This allows us to assume that the electrons remain almost thermally distributed at all times, even though they do not actually relax back to equilibrium.